Acoustic Propagation and Scattering within Sand Sediments: Laboratory Experiments, modeling based on porous media theory, and comparisons to SAX99 results.

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LONG-TERM GOALS

The long-term goal is to develop accurate models for propagation within shallow water ocean sediments for a broad range of frequencies.

OBJECTIVES

As part of the Sediment Acoustics Experiment 1999 (SAX99) several researchers measured sound speed and attenuation. Those sound speed and attenuation results have been compared to the frequency dependence predicted by Biot theory. The comparisons indicate that the variation of sound speed with frequency is well modeled by Biot theory as frequency increases, but the variation of attenuation with frequency deviates from Biot theory as frequency increases [1]. Examination of received waveforms has lead to the hypothesis that this deviation is due to increased scattering a high frequencies that is not accounted for in the present version of Biot theory. The objective of the present work is to determine whether the discrepancy between the measured attenuation and that predicted by Biot theory can be explained by the presence of scatterers or whether a theory which accounts for the unconsolidated nature of the sediment such as that suggested by Buckingham[2] is necessary to properly model the sound propagation.

APPROACH

In order to resolve this issue, laboratory measurements of both sound speed and attenuation were made in well-sized, unconsolidated, fluid-saturated sand sediments using the SAX99 diver-deployed attenuation array. In addition to minimizing experimental costs, use of this system allows us to relate the type of received signals seen in the laboratory to those seen in SAX99. The attenuation array is capable of measuring sound speed and attenuation from 80 kHz to ~260 kHz. For the upcoming Sediment Acoustics Experiment 2004 (SAX04), a second array is being developed and is capable of measuring sound speed and attenuation in the frequency band from 40 kHz to 100 kHz. The array is being used to both extend the frequency range of the laboratory experiments and to evaluate the performance of the array in preparation for deployment during SAX04.

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The sediment chosen for this experiment is composed of spherical glass beads sorted such that the diameter of the beads are in the narrow range of 0.30 – 0.43 mm. For unconsolidated glass bead sediments, both the tortuosity and the permeability are determined by the porosity of the sediment greatly simplifying the characterization of the sediment. Both the bulk modulus and the mass density of the grains were determined by the manufacturer leaving only the porosity to be measured in the laboratory. The use of this glass bead sediment insures that there are no large discrete scatterers present and, if the excess attenuation observed in SAX99 is entirely due to scattering, should exhibit variations in both sound speed and attenuation that are consistent with the predictions of Biot theory.

For the frequency range of interest, according to Biot theory a water-saturated glass bead sediment should exhibit very little sound speed dispersion over the frequency range of the two attenuation arrays. Although it is not possible to change the frequency range of the transducer arrays, Biot theory states that the frequency range over which the most significant dispersion occurs is determined by the viscosity of the fluid and the permeability of the sediment. This suggests that by using a pore fluid with a higher viscosity, it should be possible to shift the dispersion into the frequency range of the transducers. This serves both as a test of Biot theory and as a means of observing more significant dispersion than would be observed in water alone. In addition to water (which has a viscosity of 0.001 kg/m·s), two silicone oils have been chosen for use in these experiments which have viscosities of 0.01 kg/m·s and 0.1 kg/m·s.

WORK COMPLETED

Measurements have been made on two of the fluid-saturated glass bead sediments: glass beads saturated with water and glass beads saturated with the Silicone oil with a viscosity of 0.1 kg/m·s. The third fluid is being held in reserve until progress has been made in understanding the results from the previous two fluids. Both sediments were prepared in large stainless steel drums and a vacuum was pulled on each to remove any bubbles which may have been added to the sediment during preparation. The sediments were also mixed and shaken to help remove bubbles. The porosity for the water-saturated glass beads was measured to be 0.384. For the oil-saturated glass beads it was not possible to measure the porosity directly, however from model fits to the data the porosity appears to be 0.36 which is consistent with the porosity for a close-packed random arrangement of spheres. Using these porosities the permeability was calculated using the Kozeny-Carmen relation and the tortuosity was determined using an expression derived by Berryman [3]. The permeability was also measured for the water-saturated glass beads using a constant head permeameter and was found to agree with the Kozeny-Carmen relation to within the uncertainty of the measurement.

The sound speed and attenuation of both sediments was measured using the SAX99 attenuation array and the results were presented at the 144th meeting of the Acoustical Society of America [4]. The SAX04 attenuation array was constructed earlier this year and measurements are currently being made using this new array in both of the sediments. The results of both Biot theory and Buckingham's grain-to-grain shearing model have been compared to the measured sound speed and attenuation. A third theory which combines both Biot's and Buckingham's models has also been considered.

RESULTS

The sound speed ratio (the ratio of the sound speed in the sediment to that in the fluid) and the attenuation for both the water-saturated glass beads and the oil-saturated glass beads measured using

the SAX99 attenuation array is shown in Fig. 1. The dashed curves in this figure are the sound speed ratio and attenuation determined from William's effective density fluid model (EDFM) using the parameters discussed in the previous section [5]. The EDFM is the limit of Biot theory when the bulk and shear moduli both approach zero, which is consistent with the values of moduli observed in unconsolidated sediments. The dashed lines in the figures are the sound speed ratios and attenuations found using Buckingham's grain-to-grain shearing model. The parameters for this model were found from a best fit to the data.

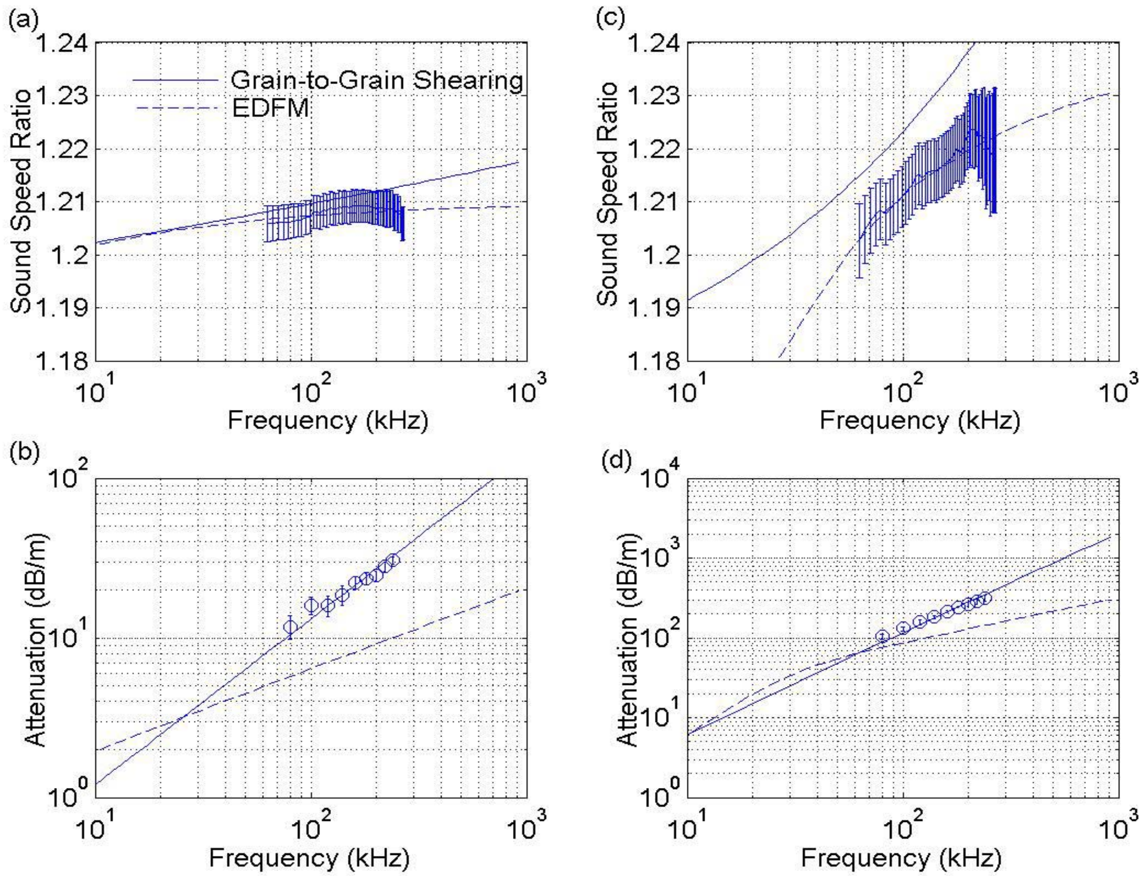

Figure 1: Sound speed and attenuation for (a) and (b) glass beads and water and for (c) and (d) glass beads and Silicone oil. The dashed line in each figure is the sound speed and attenuation predicted by Biot Theory while the solid line is a model fit using Buckingham's grain-to-grain model.

Consistent with the measurements made during SAX99, the dispersion in the sound speed is captured by Biot theory while there is a discrepancy between the measured attenuation and that predicted by Biot theory. For the glass beads and silicone oil sediment the dispersion in the sound speed was shifted into the frequency range of the transducer array indicating that Biot theory is able to account for the frequency dependence of the sound speed. However, as in the SAX99 data, for both sediments the attenuation depends linearly on the frequency as opposed to an $f^{1/2}$ dependence predicted by Biot theory. This excess attenuation is present in the absence of scatterers, however the waveforms observed in the glass bead sediments do not show the complex, variable and extended structure that was observed in the SAX99 measurements which were made using the same array [1]. This indicates

that although there appears to be an additional attenuation mechanism in the glass bead sediment that is not explained by Biot theory, scattering by discrete scatterers may be at least partially responsible for the propagation loses in the SAX99 sediment.

In Fig. 1, although Buckingham's grain-to-grain shearing model does not fit the sound speed data well, it does handle the attenuation better than Biot theory. This success of Biot theory in modeling the sound speed variation and the success of the Buckingham model in modeling the attenuation suggests a possible alternative which would combine these two models. The EDFM does not account for interactions at the grain contacts while Buckingham's model fails to account for fluid flow in the pore spaces. The third model, which will be referred to as the G-to-G/EDFM, takes both attenuation mechanisms into account using the framework of both Biot theory and Buckingham's model. Using the sediment properties measured during SAX99 and a best fit to determine the grain-to-grain shearing constants, Fig. 2 compares the G-to-G/EDFM to the SAX99 sound speed and attenuation data.

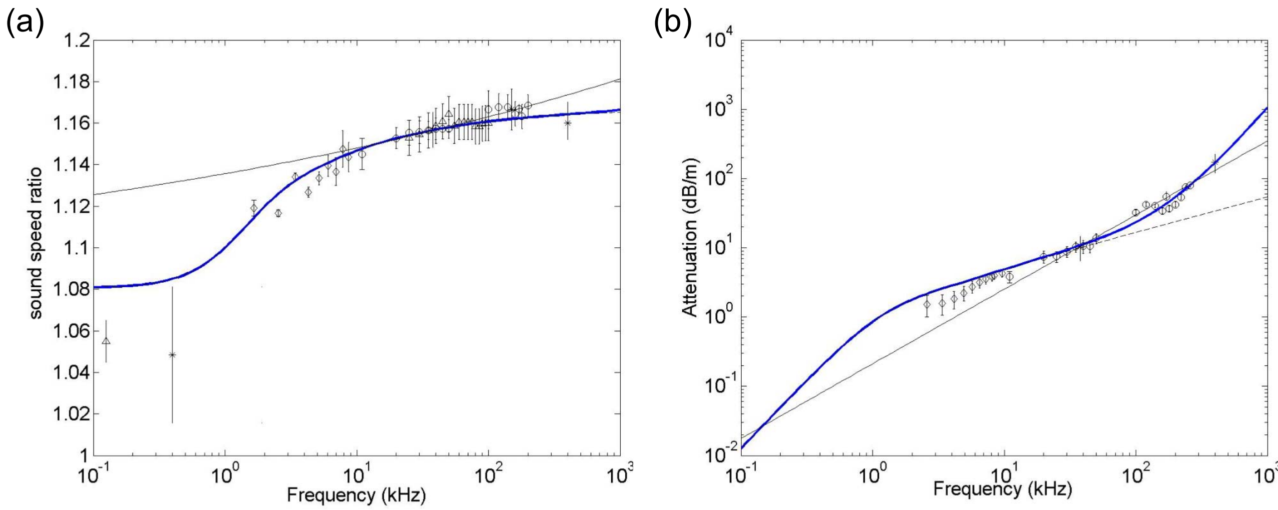

Figure 2: (a) Sound speed ratio and (b) attenuation for the sediment measured during SAX99. The dashed line is the sound speed and attenuation predicted by Biot theory. The solid black line is the best fit of Buckingham's grain-to-grain shearing model. The thick blue line is the best fit of the combined G-to-G/EDFM.

IMPACT/APPLICATIONS

These results suggest that a complete model of sound propagation in fluid-saturated, unconsolidated sediments must account for both relative motion of the pore fluid and an as yet unidentified attenuation mechanism. This additional attenuation mechanism may be due to the interactions between the sediment grains as suggested by Buckingham, however at this point the source of the attenuation remains unknown. Also, an examination of the waveforms in both the laboratory experiments and the SAX99 measurements suggests that scattering due to discrete scatterers may still be significant contributor to attenuation in ocean sediments.

RELATED PROJECTS

This research explores issues raised during SAX99, specifically the nature of attenuation in fluid-saturated, unconsolidated sediments. By using the SAX99 attenuation array, the data collected in the laboratory experiments can be compared directly to the data collected during SAX99.

The results of this research have a direct bearing on the upcoming SAX04 in that they suggest that attenuation due to scattering within the sediment should be examined in greater detail. During SAX04 we plan to collect and characterize the scatterers found in the sediment at the experiment site and use this information to develop models which take into account this attenuation source. Also a lower frequency transducer array has been constructed which will be deployed during SAX04. By using this array in the laboratory sediments, data can be collected for lower frequencies and the performance of the array can be evaluated prior to deployment in SAX04.

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